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iNET Preamble Detector Performance in the Presence of Multipath Interference

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14. ABSTRACT

Multiple preamble detectors are presented and applied to an SOQPSK-TG modulated signal in simulation. Multipath interference, additive white Gaussian noise, and frequency offsets are applied to the signal before detection is attempted. Simulation results are compared. A non-coherent post-detection integration (NCPDI) detector considered in this paper demonstrates the best detection performance for a reduced complexity.

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iNET PREAMBLE DETECTOR PERFORMANCE IN THE PRESENCE OF MULTIPATH INTERFERENCE

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ABSTRACT

Multiple preamble detectors are presented and applied to an SOQPSK-TG modulated signal in simulation. Multipath interference, additive white Gaussian noise, and frequency offsets are applied to the signal before detection is attempted. Simulation results are compared. A non-coherent post-detection integration (NCPDI) detector considered in this paper demonstrates the best detection performance for a reduced complexity.

INTRODUCTION

This paper will consider data-aided synchronization and equalization for aeronautical telemetry. The integrated Network Enhanced Telemetry (iNet) standard [1] describes a packet-based mode of data transfer, useful for telemetry downlinks. The standard defines each packet as consisting of three fields: a preamble, an attached sync marker (ASM), and data bits in the form of an LDPC codeword.

Data-aided synchronizers and equalizers operate by comparing a copy of a preamble (a known sequence) to the received copy. The frequency, phase, and timing offset can be estimated in the synchronizer. Previous work on this idea using iNET formatted SOQPSK-TG is shown in [2]. The comparison is used in the equalizer to estimate the impulse response of the channel in discrete time, which is then used to compute the optimum equalizer coefficients. See [3] for a more detailed example of this.

The first challenge in either operation lies in determining the starting location of the preamble for each packet within the received signal. Whatever detector is employed to find the preamble must be robust enough to detect it reliably given unknown channels and frequency offsets. The detected preamble can then be used in the synchronizers or equalizers.

This paper will focus on preamble detection in SOQPSK-TG modulated data streams in the iNET format.

SIGNAL MODEL

The transmitted signal, $s(t)$, uses an SOQPSK-TG modulated carrier. Details on SOQPSK-TG are shown in [4] and [5]. Post-modulation, the signal is convolved with a frequency selective channel. In addition, a frequency offset and additive white Gaussian noise is added. The received signal is of the form

$$r[n] = \left[\sum_{-N_1}^{N_2} h[k]s[n-k] \right] e^{j\omega_0 n} + w[n] \tag{1}$$

where $h[n]$ is the impulse response of the unknown channel with support on $-N_1 \leq n \leq N_2$, $s[n]$ are the received samples of the SOQPSK-TG signal, ω_0 is the unknown frequency offset, and $w[n]$ are samples of a zero-mean complex-valued white Gaussian noise process.

The bit pattern of the preamble must also be considered and chosen. From analysis in [6], the chosen sequence is CD98HEX repeated eight times. This pattern was chosen because the repetition allowed fast acquisition in burst-mode transmissions.

THE MAXIMUM LIKELIHOOD PREAMBLE DETECTOR

Barker [7] showed that preamble detection (also called "frame synchronization") was possible by maximizing a simple correlation function. Massey expounded on this by deriving the maximum likelihood (ML) preamble detector searching for binary data in Gaussian noise [8]. Gansman *et al.* addressed unknown carrier frequency and phase in the received signal [9]. Choi and Lee, who derived several ML functions examined in this paper, developed an ML detector that has a "double correlation" structure [10]. The Choi and Lee functions provide better performance over a wider frequency offset than the Gansman preamble detector [9].

Pedone *et al.* [11] showed a preamble detector from a series of balanced generalized post detection integration (B-GPDI) operations. Their work used a non-coherent combination of coherent partial correlations (also called "integrations"). This paper will utilize this structure, called non-coherent post detection integration (NCPDI) to derive two lower-complexity preamble detectors to be examined.

SIMPLE PREAMBLE DETECTOR

The basic preamble detector structure in the literature consists of a correlation function that compares a known and stored copy of the preamble to the received samples. For this paper, let $p[n]$, $0 \leq n < L_p$ be the stored copy of the preamble of length $L_p - 1$. In the AWGN case (where no frequency-selective channel or frequency offset is applied), the received signal takes the form $r[n] = s[n] + w[n]$. The correlation function is calculated as

$$L_0[u] = \left| \sum_{n=u}^{u+L_p-1} r[n]p^*[n-u] \right| \tag{2}$$

This function is evaluated once for each received sample. Over each packet length, the maximum value of L_0, called i_{max}, is chosen as the starting location of the preamble. If the true location of the preamble for a given packet is at sample i, then the preamble detector has correctly decided the starting location of the preamble if $i_{max} = i$.

This detector has the advantage of being moderately simple in complexity. It required $4L_p + 2$ real-valued multiplications and a single square root operation.

CHOI-LEE PREAMBLE DETECTORS

In real telemetry, assuming an AWGN environment is inadequate to achieve good performance. The added interference of the frequency offset causes the simple preamble detector in (2) to fail; the frequency offset introduces destructive cancellation in the summation.

The Choi and Lee described “double correlation” functions exhibit good performance despite unknown channel and frequency offset.

The first function (called $L_1(u)$ in [10]) has the form

$$L_{\text{CL-1a}}[u] = \sum_{i=1}^{L_p-1} \left\{ \left| \sum_{k=i}^{L_p-1} r^*[u+k]p[k]r[u+k-i]p^*[k-i] \right| - \sum_{k=u+i}^{u+L_p-1} |r[k]||r[k-i]| \right\} \tag{3}$$

This function is computationally complex. It requires $\frac{1}{2}[13L_p(L_p-1) + 4L_p]$ real-valued multiplications and $2L_p - 1$ square root operations for each index u.

If unknown frequency-selective multipath interference is also applied to the transmitted signal, the correction term in (3) can be omitted, resulting in the second Choi-Lee detector function:

$$L_{\text{CL-1b}}[u] = \sum_{i=1}^{L_p-1} \left\{ \left| \sum_{k=i}^{L_p-1} r^*[u+k]p[k]r[u+k-i]p^*[k-i] \right| \right\} \tag{4}$$

This function needs only $6L_p(L_p-1)$ real-valued multiplications, and L_p-1 square root operations.

Choi and Lee proposed two other functions that result from using only the $i = 1$ terms in (3) and (4) to produce, respectively:

$$L_{\text{CL-2}}[u] = \left| \sum_{k=1}^{L_p-1} r^*[u+k]p[k]r[u+k-1]p^*[k-1] \right| - \sum_{k=u+1}^{u+L_p-1} |r[k]||r[k-1]| \tag{5}$$

and

$$L_{\text{CL-3}}[u] = \left| \sum_{k=1}^{L_p-1} r^*[u+k]p[k]r[u+k-1]p^*[k-1] \right| \tag{6}$$

The $L_{\text{CL-2}}$ function requires $15L_p-13$ real-valued multiplications and L_p+1 square root operations for each index u. The $L_{\text{CL-3}}$ function requires $12(L_p-1)$ real-valued multiplications and a single square root operation for each index u.

For all of these functions, as in the AWGN case, the maximum value is found over the length of a packet. This is the decided location of the preamble.

NCPDI PREAMBLE DETECTORS

An inherent disadvantage of the Choi and Lee detectors is the overwhelming computational complexity required for each sample value u. Running these detectors in real-time is a difficult proposition at best; it is desirable to find a reduced-complexity detector that will achieve good performance even in unknown multipath interference and frequency offset environments.

We adapt the non-coherent post-detection integration (NCPDI) detector developed in [11]. We first write the correlation interval as $L_p = L_{\text{PDI}}L_{\text{coh}}$ to separate the correlation into two sections: coherent correlations of length L_{coh}, and L_{PDI} non-coherent sums of the L_{coh} combinations. This is written as

$$L_{\text{NCPDI}}[u] = \sum_{k=0}^{L_{\text{PDI}}-1} \left| \sum_{m=kL_{\text{coh}}}^{(k+1)L_{\text{coh}}-1} r[u+m]p^*[m] \right|^2 \tag{7}$$

Taking advantage of the chosen preamble structure, we set $L_{\text{coh}} = 32$. This is the length of the repeating sequence in the preamble (at 2 samples per bit). Choosing this value then forces $L_{\text{PDI}} = 8$. Further taking advantage of the fact that $p[n]$ is the form of the modulated bit pattern repeated eight times, let $q[n]$ be the SOQPSK-TG modulated samples of a single repeating section of the preamble (corresponding to the bits CD98HEX), with length L_q. With some variable manipulation, we can write the function as

$$L_{\text{NCPDI-1}}[u] = \sum_{k=0}^{7} \left| \sum_{l=0}^{L_q-1} r[u + kL_q + l]q^*[l] \right|^2 \tag{8}$$

This function requires $4L_q + 16$ real-valued multiplications and zero square root operations for each index u.

A simplified version of this detector quantizes the possible values of $q[n]$ to ± 1, $\pm j$, and $\frac{1}{\sqrt{2}}(\pm 1 \pm j)$. This function, denoted $L_{\text{NCPDI-2}}$, requires only 32 real-valued multiplications and zero square root operations for each index u.

PERFORMANCE

At $N = 2$ samples per bit and using the preamble structure shown above, Table 1 lists the proposed functions and their computational requirements for each index u. As was desired, the NCPDI detectors have a significantly reduced computational complexity.

Table 1: Computational Complexity of the Candidate Preamble Detectors
For a Sample Rate of $N = 2$ Samples/Bit

L[u]	**# Real-Value Mults.**	**# Square-Roots**
$L_0[u]$	1,026	1
$L_{\text{CL-1a}}[u]$	424,832	511
$L_{\text{CL-1b}}[u]$	391,680	255
$L_{\text{CL-2}}[u]$	3,827	257
$L_{\text{CL-3}}[u]$	3,060	1
$L_{\text{NCPDI-1}}[u]$	1,040	0
$L_{\text{NCPDI-2}}[u]$	32	0

All of these functions were tested in simulation, and performance was gauged by the mean and variance of $i - i_{max}$. Simulations were performed with three different channel impulse responses, all of which were captured during channel sounding experiments at Edwards AFB, California [12]. See Figure 1 for the frequency responses of the channels. The simulations were run with a bit rate of 10.3125 Mbits/s, using SOQPSK-TG modulation at a sample rate of $N = 2$ two samples/bit. Frequency offsets of $\Delta f = 0$ Hz and $\Delta f = 50$ KHz were applied.

As shown in figures 2a - 2f, the detectors using $L_{\text{CL-1a}}$, $L_{\text{CL-1b}}$, $L_{\text{NCPDI-1}}$ and $L_{\text{NCPDI-2}}$ exhibited great performance in all test scenarios. The mean error for the detectors using these functions was very nearly zero, even in the high frequency offset environments.

Some caution must be exercised when examining the variance results. Because many of the index errors were zero the number of errors from which the variance estimate is determined is small,

causing the estimate to be somewhat unreliable. This is especially true for the $L_{\text{CL-1a}}$ and $L_{\text{CL-1b}}$ based detectors, who had nearly zero errors across the board.

However, we can draw general conclusions from the results. The $L_{\text{CL-1a}}$ and $L_{\text{CL-1b}}$ based detectors had the best performance, followed closely by the $L_{\text{NCPDI-1}}$ and $L_{\text{NCPDI-2}}$ based detectors. The $L_{\text{CL-2}}$ and $L_{\text{CL-3}}$ detectors came third in performance, although their error variances were quite different from channel to channel.

The correction term found in in $L_{\text{NCPDI-1}}$ and $L_{\text{CL-2}}$ had a curious effect on the detector performance. Depending on the channel, it either improved or degraded system performance when compared to the $L_{\text{CL-1b}}$ and $L_{\text{CL-3}}$ detector systems. It appears that the varying ISI from channel to channel coupled with the correction term causes detector performance to vary, as well.

As expected, the simple detector based on L_0 showed good performance when the frequency offset $\Delta f = 0$ Hz, but had terrible performance when the frequency offset $\Delta f = 50$ KHz.

CONCLUSIONS

We have shown that of the candidate functions listed, the reduced complexity NCPDI detector provides the best tradeoff between performance and computational complexity. It is also shown that preamble detectors based on SOQPSK-TG samples can have good performance, despite an unknown frequency offset and unknown ISI.

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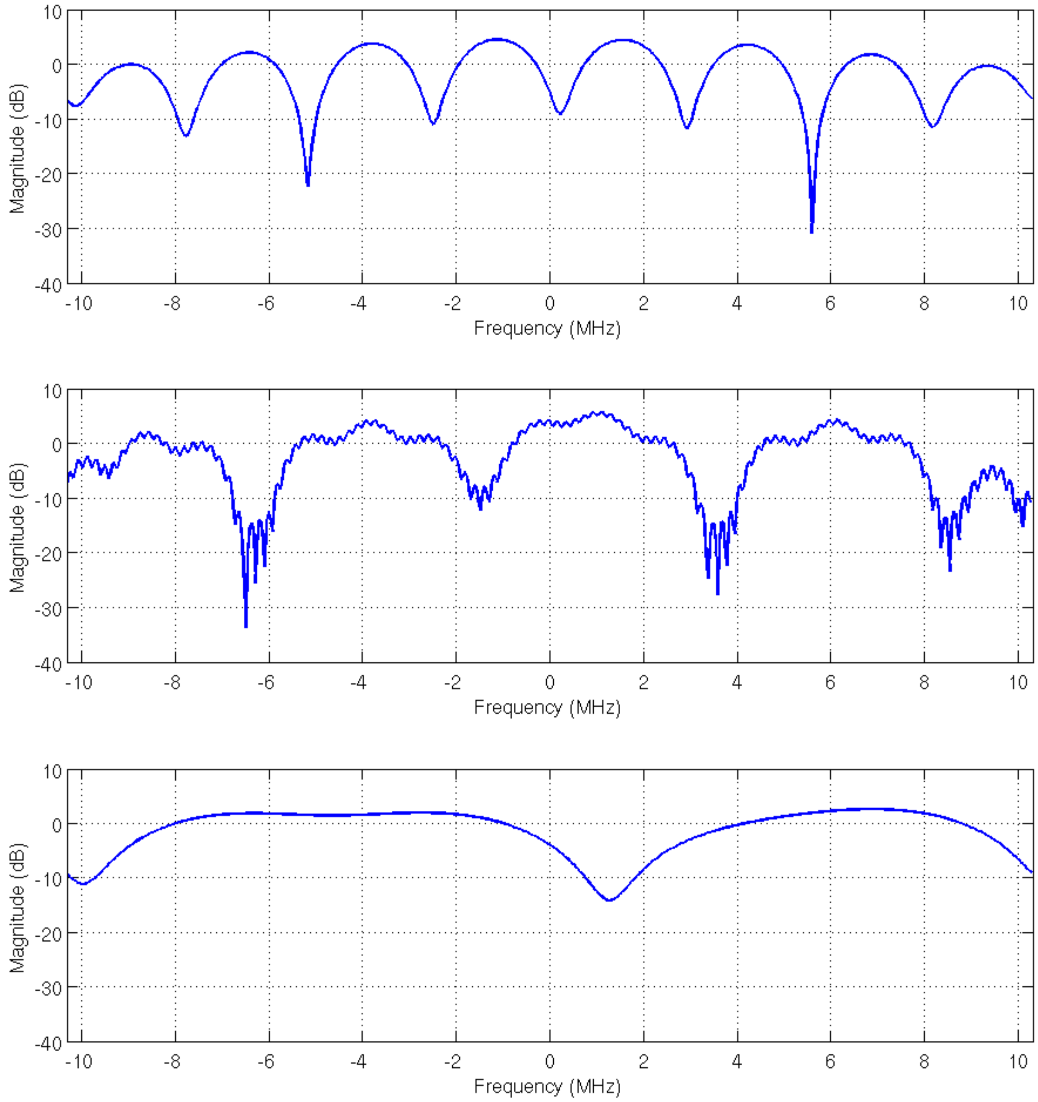
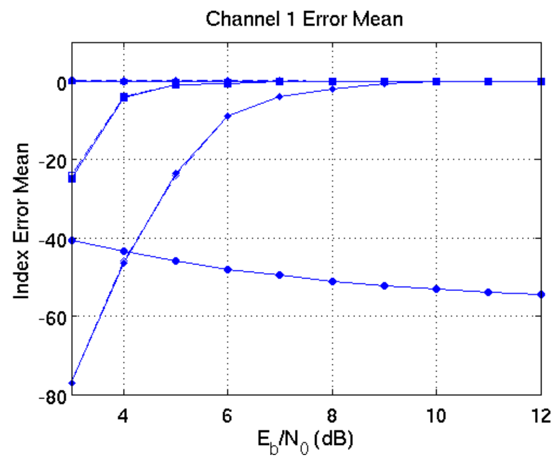
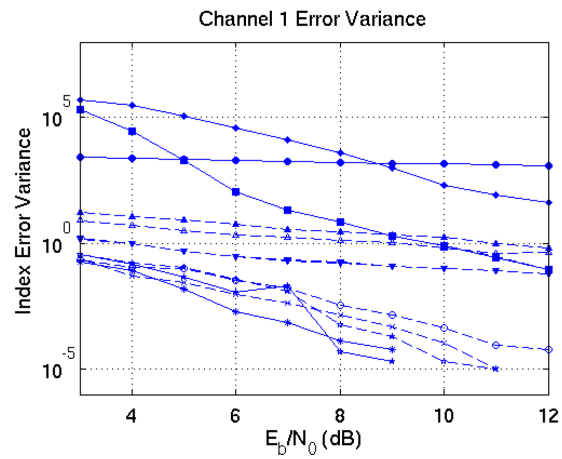


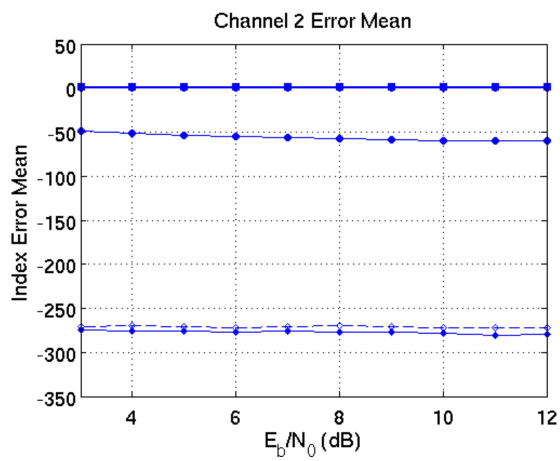
Figure 1: The example channels from channel sounding experiments at Edwards AFB: (top) a length-9 channel from the flight line; (middle) a length-19 channel from take-off; (bottom) a length-5 channel from low-elevation angle "up and away" flight.



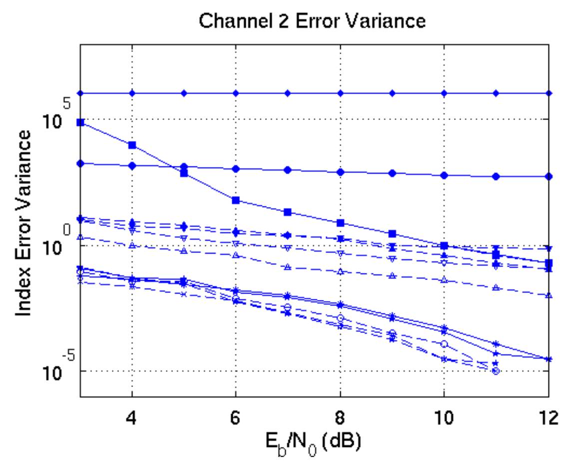
(a) Error means for simulations with channel 1



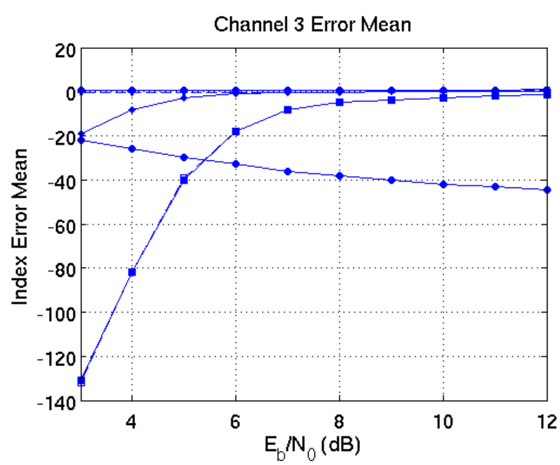
(b) Error variances for simulations with channel 1



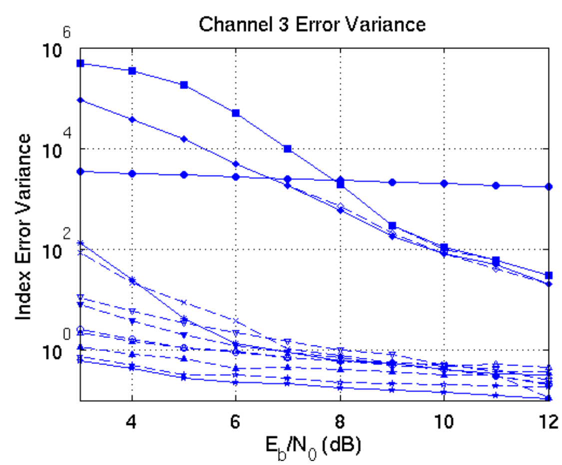
(c) Error means for simulations with channel 2



(d) Error variances for simulations with channel 2



(e) Error means for simulations with channel 3



(f) Error variances for simulations with channel 3

Figure 2: All simulation results. See figure 3 for plot legend.

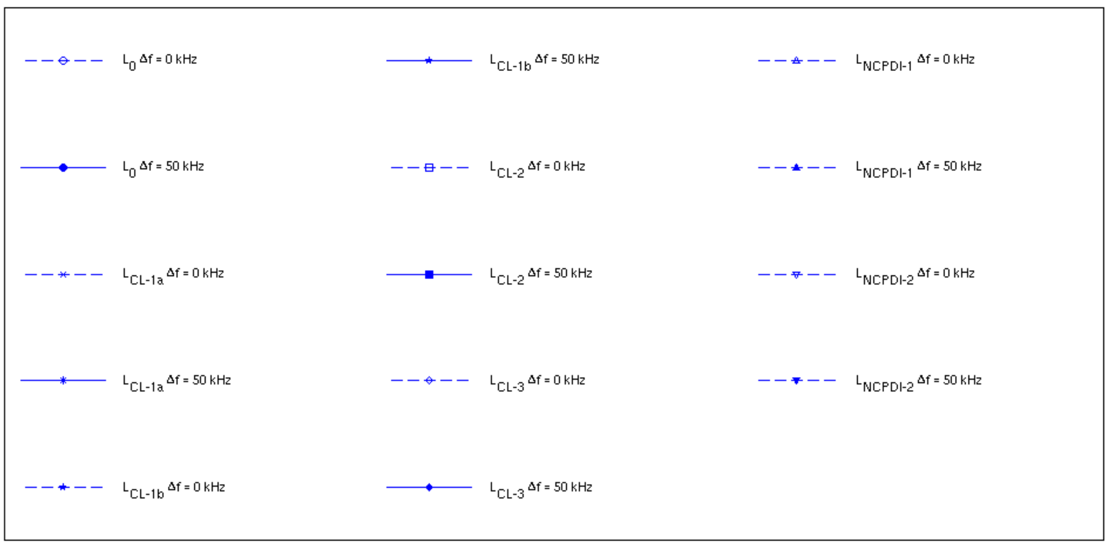


Figure 3: Plot legend for figures 2a - 2f.